System Simulation and Coverage Analysis of 5G NR Communication System Based on 700 MHz Frequency Band

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Abstract. 700 MHz is the golden frequency band recognized by the global communications industry and the main frequency band of 5G for global operators. Currently, countries around the world are seizing 5G opportunities and deploying networks on a large scale. Due to the characteristics of low 700 MHz spectrum, wide coverage, and low cost of network construction, it will play an important role in the construction of 5G networks. As a refined network planning and forecasting method, the ray tracing transfer model has been provided by foreign manufacturers for a long time, such as Aster in France and WinProp in Germany. This paper proposes a ray tracing propagation model LiShuttle based on stereo space search, and applies it to the system simulation in the 700 MHz frequency band. Compared with other ray tracing models, LiShuttle can complete direct, reflected, and diffracted path searches by emitting full-dimensional and omni-directional rays, and has the characteristics of flexible configuration and accurate simulation. Based on the LiShuttle ray tracing propagation model, this paper has carried out 700 MHz link budget, outdoor remote simulation, area coverage simulation and building stereo simulation, and comprehensively analyzes its coverage capability, which is full of reference value and guiding significance for the planning and optimization of 5G NR network.

Keywords: 700 MHz · Ray tracing · LiShuttle · System simulation · Coverage analysis

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1 Introduction

700 MHz is not only considered to be the golden frequency band of 5G, but this frequency band has always been called the "digital dividend" in the wireless communication system. Due to its low frequency spectrum, long coverage, and strong deep coverage, this frequency band is suitable for large-area network coverage and has the lowest networking cost. On March 19, 2020, at the 87th access network plenary meeting of 3GPP, the China Radio and Television 700 MHz frequency band 2 * 30/40 MHz technical proposal was adopted and included in the 5G international standard, becoming the world's first 5G low frequency band (Sub-1 GHz) The large bandwidth 5G international standard, numbered TR38.888, NR format is n28. With the release of the 700 MHz "digital dividend", countries around the world are seizing the opportunity of 5G construction, and the global 700 MHz frequency band industry chain is developing rapidly.

The Ministry of Industry and Information Technology of China has issued the "Notice of the Ministry of Industry and Information Technology on Adjusting the Plan for the Use of the 700 MHz Frequency Band" on April 1, 2020, and made adjustments to the plan for the use of the 700 MHz frequency band, clearly changing the frequency of the 702–798 MHz band. Use planning adjustment for mobile communication systems, and use 703–743/758–798 MHz frequency band planning for frequency division. On January 26, 2021, China Mobile and China Radio and Television signed a "5G Strategy" cooperation agreement in Beijing, officially launching the joint construction and sharing of 700 MHz 5G networks.

Domestic and foreign experts have also conducted related research on the 700 MHz frequency band and 5G NR system. In this paper, the related research on 700 MHz is carried out. The literature mainly introduces the necessity of cooperation between 700 MHz and 2.6 GHz [1]. In addition, the literature mainly elaborated the 700 MHz network technical architecture from three aspects of the wireless access network, bearer network and core network, and analyzed the advantages and disadvantages of the 700 MHz frequency band [2]. There is also a paper that analyze the application of different propagation models in different scenarios, such as the close-in (CI) free space reference distance model, the floating intercept model (FI), and the alpha-beta-gamma (ABG) model [3].

Based on the LiShuttle ray tracing propagation model, this paper conducts system simulation and coverage analysis of 700 MHz. Through simulation and analysis, it can guide the planning, construction, maintenance and optimization of 5G NR in the 700 MHz frequency band. In addition, a performance comparison was made with the lower 2.6 GHz of the 5G NR mid-band.

2 The System Simulation and Frequency Analysis of 700 MHz

2.1 5G System Simulation Based on LiShuttle Ray Tracing Model

Network Simulation and Propagation Model

The purpose of wireless network system simulation is to evaluate wireless network coverage and capacity indicators through simulation calculations to achieve the purpose of simulating actual network characteristics. Then, the rationality of network construction can be analyzed based on the simulation results. At the same time, it provides references for site deployment location, broadcast weight optimization, RF parameter optimization, etc. It is an important means of network evaluation and prediction. The general flow of the simulation is shown in Fig. 1.

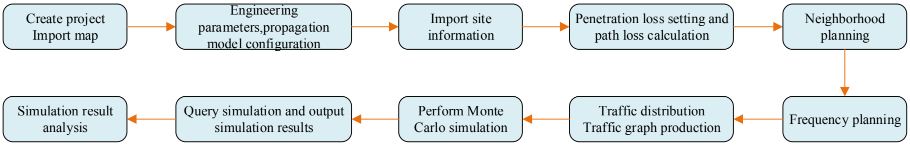

Fig. 1. Wireless network simulation flow chart

In the above process, the setting of the propagation model is the most important link, which has the greatest impact on the simulation results. The propagation model needs to calculate the propagation loss of radio waves under a certain environment or propagation path. In terms of research methods, the communication models currently used are mainly divided into two categories: one is a statistical model based on a large amount of test data, also called an empirical model. The common ones are Okumura-Hata, Cost231-Hata, Lee, Spm, Uma, etc. The other type is a deterministic model calculated based on electromagnetic theory. The most representative one is the three-dimensional ray tracing model. The common ray tracing models in the industry mainly include Aster in France, Volcano in France, and WinProp in Germany [4].

LiShuttle Ray Tracing Model

This paper proposes a new three-dimensional ray tracing propagation model LiShuttle, which is based on geometric optics principles and three-dimensional space search, which can accurately simulate the direct, reflection, diffraction, and transmission phenomena of electromagnetic waves in space propagation. It is a refined propagation prediction model that can accurately reflect the coverage of wireless signals on the existing network. The realization of the LiShuttle ray tracing model is mainly divided into two major steps: path search and loss calculation.

In the path search, the macro cell, micro cell, and mini cell must be judged first. Then, determine the type of multipath that needs to be calculated according to the cell type. The main types of multipath calculated by this ray tracing model are: direct radiation, horizontal reflection, roof diffraction, horizontal plane diffraction and transmission. The flowchart of LiShuttle path search is shown in Fig. 2, then Tx is used here to refer to transmitter.

After completing the path search in the calculation area, it is necessary to calculate the path type of each grid in the area to calculate the path loss. This model takes into account all factors such as base station parameters, terminal parameters, ground features, and multipath loss when calculating. The specific calculation formulas are formula 1 and formula 2:

$$PL = K_0 + K_{near}\log(d_{3d}) + 20\log(f_c) + \Delta K_{far}f(d_{2d}) + \partial_{\mathrm{ref}}\mathrm{PL}_{ref} + \partial_{dif}\mathrm{PL}_{dif} \quad (1)$$

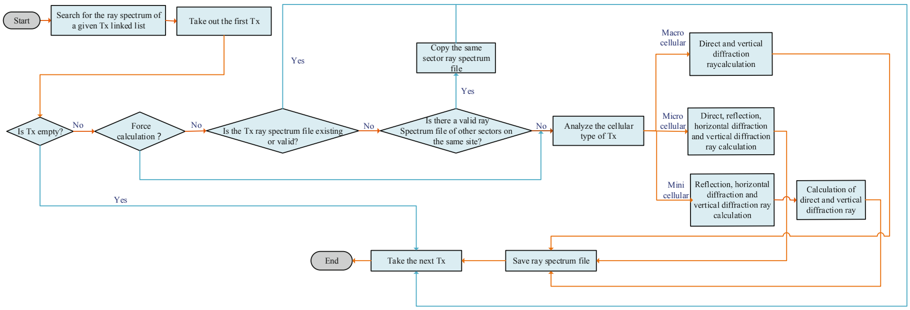

Fig. 2. The flow chart of LiShuttle's path search

In formula 1,

$$f(d_{2d}) = \begin{cases} 0 & d_{2d} <= d'_{bp} \\ \log \frac{d_{3d}}{\sqrt{d'_{bp} + (h_{bs} - h_{ut})^2}} & d_{2d} > d'_{bp} \end{cases} \tag{2}$$

In the formula, K_0 is the fading constant, K_{near} is the coefficient of the near field, K_{far} is the coefficient of the far field, ∂_{dif} is the coefficient of diffraction, ∂_{ref} is the coefficient of reflection.

After the path loss is calculated, the signal level value at the receiving point is obtained by the following formula, which is calculated according to formula 3:

$$\mathrm{P}_r = P_t + G - PL - L_{body} - SFM - FFM - OTA \tag{3}$$

In formula 3, P_r is the received signal level value, P_t is the transmitted signal level value, G is the antenna gain, PL is the path loss, L_{body} is the human body loss, SFM is the shadow fading margin, FFM is the fast fading margin, OTA is the Over-the-Air loss.

2.2 Analysis of 700 MHz Frequency Characteristics

Analysis of Electromagnetic Wave Propagation Loss in Free Space
The propagation of electromagnetic waves in free space can be derived from the Friisian transmission equation [5]. The Friesian transmission equation is:

$$\mathrm{P}_r = \frac{P_t \mathrm{G_t G_r} \lambda^2}{(4\pi)^2 d^2} \tag{4}$$

In formula 4, P_r is the received power, P_t is the transmit power, G_t and G_r represents the transmit antenna gain and the receive antenna gain, λ s the carrier wavelength, d is the distance between the transmitting and receiving antennas.

From the above formula, it can be concluded that the propagation loss of electromagnetic waves in free space is:

$$\begin{aligned} PathLoss &= 10\log(\frac{P_t}{P_r}) = 10\log(\frac{4\pi d}{\lambda})^2 \\ &= 32.45 + 20\lg f + 20\lg d \end{aligned} \tag{5}$$

In formula 5, *PathLoss* is the free space propagation loss, f is the operating frequency of electromagnetic waves.

It can be seen from formula 1.5 that the lower the frequency of the 700 MHz electromagnetic wave signal is, the smaller the space loss will be.

Analysis of Wavelength and Diffraction Ability

The formula between wavelength and frequency:

$$\lambda = \frac{c}{f} \tag{6}$$

c: Speed of light, unit: m/s, the speed of light is a constant, approximately equal to 3×10^8 m/s in vacuum.
f: Frequency, unit: Hz.
λ: wavelength, unit: m.

According to the relationship between the wavelength and frequency of electromagnetic waves, the wavelength λ is inversely proportional to the frequency f. If the frequency is lower, the wavelength is longer, the diffraction ability is stronger, and the coverage area is wider. Compared with other 5G frequency bands such as 2.6 GHz, 3.5 GHz, 4.9 GHz, the 700 MHz frequency band has a huge wavelength advantage and a wider coverage. Under the goal of achieving full wireless communication network coverage, fewer base stations are required to use this frequency band, which can greatly reduce network construction and operating costs.

Analysis of the Doppler Effect

Mobile communication customers will suffer from the inconvenience caused by the phenomenon of "Doppler frequency offset" under high-speed operating environment. This effect will cause a serious deviation of the frequency received by the terminal, which will affect the demodulation performance of the receiver [6].

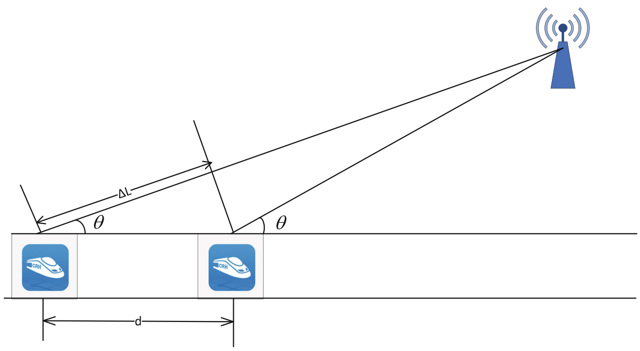

Fig. 3. Schematic diagram of Doppler frequency offset in the high-speed rail scenario

Analyze the Doppler frequency deviation according to the high-speed rail Doppler diagram in Fig. 3. Assuming that the speed of the high-speed rail is v, the angle between the train and the signal transmission direction is θ, and after a certain period of time Δt, the train's running distance is d, then the distance difference between the signals received by the user can be calculated as ΔL is:

$$\Delta L = d\cos\theta = v \cdot \Delta t \cos\theta \tag{7}$$

Then the phase change of the received signal is:

$$\Delta\varphi = \frac{2\pi\Delta L}{\lambda} = \frac{2\pi v \Delta t}{\lambda}\cos\theta \tag{8}$$

From the above analysis, it can be concluded that the Doppler frequency shift is:

$$f_d = \frac{1}{2\pi} \cdot \frac{\Delta\varphi}{\Delta t} = \frac{v}{\lambda} \cdot \cos\theta = \frac{f}{c} \cdot v \cdot \cos\theta \tag{9}$$

In formula 9, c is the speed of light, and the value is 3×10^8 m/s. It can be seen from the formula that the faster the speed and the higher the frequency, the greater the Doppler frequency deviation. According to the calculation, the relationship between the speed of the high-speed rail and the frequency bands of the 5G network can be obtained, as shown in Table 1.

Table 1. The influence of train speed and frequency on Doppler frequency deviation

Speed（km/h）	700M Frequency deviation（Hz）	1.8G Frequency deviation（Hz）	2.6G Frequency deviation（Hz）	3.5G Frequency deviation（Hz）
200	259	667	963	1296
250	324	833	1204	1620
300	389	1000	1444	1944
350	454	1167	1685	2268
400	518	1333	1926	2592
450	583	1500	2166	2916
500	648	1666	2407	3240

It can be seen from Table 1 that under the same frequency, the faster the train speed is, the greater the Doppler frequency deviation will be; if the train speed is the same, the higher the frequency is, the greater the Doppler frequency deviation will be. Therefore, choosing the 700 MHz frequency band can effectively reduce the Doppler frequency offset when deploying base stations in high-speed rail scenarios.

Small Delay in FDD Duplex Mode

In 5G, the duplex mode includes two modes: FDD and TDD. FDD receives and transmits on two separate symmetric frequency channels, and uses guard bands to separate the receive and transmit channels; TDD, time division duplex, uses time to Separate the receive and transmit channels. It is carried out in one channel [4]. In a TDD mobile communication system, different time slots of the same frequency carrier are used for reception and transmission as channel bearers, and time resources are allocated in two directions. In TDD mode, some uplink data feedback needs to wait for the corresponding uplink time slot. Generally, the TDD system allocates fewer time slots to the uplink, so the feedback waiting time of TDD is longer than FDD.

The 700 MHz frequency band adopts the FDD standard, while other 5G frequency bands such as 2.6G, 3.5G and 4.9G all adopt the TDD standard. When only the air interface delay is considered, the air interface delay of the 700 MHz frequency band is theoretically less than Other 5G frequency bands.

3 Analysis of 700 MHz Simulation Coverage

3.1 Simulation Parameter Configuration

Introduction to the Simulation Area

The selected area for this simulation is the Zhujiang New Town area of Guangzhou, which is a super dense scene with an area of 6.12 Km^2. The distribution of wireless base stations in the Zhujiang New City area: 242 cells with a total of 99 base stations of 2.6 GHz; 68 cells with a total of 27 base stations of 700 MHz.

Fig. 4. Situation of the simulation area

Simulation Parameters

The map used in this simulation is a planet electronic map with the precision of 5 m. The propagation model is the LiShuttle ray tracing model. In the simulation, the constant K_0 is set to 28, the near field coefficient K_{near} is set to 22, the far field coefficient K_{far} is set to 40, and the maximum number of reflections is 4. The maximum diffraction order is 2. The parameters of this system simulation are shown in Table 2.

Table 2. Parameter setting of LiShuttle propagation model

NR parameters	2.6G	700M	Impact index	Parameter Description
Propagation model	LiShuttle Ray tracing model		Indicators of each dimension	Propagation model accuracy affects simulation accuracy
map	5m precision three-dimensional electronic map		Indicators of each dimension	Electronic map affects simulation accuracy
bandwidth（MHz)	100	30	rate	Cell bandwidth
Subcarrier spacing (kHz)	30	15	rate	Subcarrier spacing
Uplink and downlink timeslot ratio	2:8	/	rate	Uplink and downlink frame ratio
Maximum number of reflections	4	4	RSRP	Maximum number of reflections for ray search
Maximum diffraction order	2	2	RSRP	Maximum diffraction number of ray search
Base station antenna transceiver number	64trx	4T4R	rate	Number of transmitting and receiving antennas on the base station side
Terminal transmit power（dBm)	16.85	20.9	RSRP、rate	Maximum transmit power of terminal
Number of terminal antennas	2T4R	1T2R	rate	Number of terminal transmitting and receiving antennas

In order to improve the accuracy of the simulation, when building-level simulation is performed, the buildings are divided into eight typical scenes. Based on on-site measurements, buildings in different scenes are set with different penetration loss and progressive loss, and different scenarios have different standards. The building penetration loss and progressive loss settings are shown in Table 3.

Table 3. Loss settings in different scenarios.

Scenes	2.6G		700M	
	First layer loss（dB）	Progressive loss(dB)	First layer loss（dB）	Progressive loss(dB)
Hospital	11.5	1.2	6	1
Hotel	10.5	1.5	6	1
Office building	11.5	1.8	6	1.2
Residential area	13.5	1.5	6	1
School	13	1.2	6	1
Shopping mall	13.5	1.5	6	1.2
Transportation hub	20	1.8	12	1.2
Large venue	20	1.8	12	1.2

3.2 Analysis of Simulation Results

Link Budget Simulation
Ten co-located cells in Zhujiang New Town are selected randomly, and the link budgets of 2.6 GHz and 700 MHz are compared and analyzed under the same conditions of transmission power, antenna and propagation model.

The results are shown in Table 4:

Table 4. Link budget results

The name of the base station cell	2.6GHz	700MHz	Difference between two means
Zhumeila Apartments	154.1267	139.7513	14.37535
Northwest of New Axis Plaza	143.5671	129.2682	14.29886
Pearl River Dijing Apartment_1	136.3937	123.1116	13.28211
Feiyu Hotel	143.9388	129.9341	14.00461
Yuancun South Street	150.0634	135.6127	14.45062
Cuihu Villa (Relocation)_1	143.5218	128.0173	15.50449
Pearl River Dijing Apartment_2	121.4908	108.7548	12.73604
Yuexiu CPPCC (relocation)	114.8379	100.7843	14.05365
Cuihu Villa (Relocation)_2	137.1835	121.7174	15.46604
South Gate of the Zoo	133.5832	118.1363	15.44695

By comparing the link calculation results of 2.6 GHz band and 700 MHz band, in the single residential area, the coverage gain of 700 MHz band is 14–15 db relative to 2.6 GHz band. At the same time, four residential areas in Table 5 are selected and the results of path loss are rendered. As shown in Fig. 5, the picture on the left is the result of 2.6 GHz, and the picture on the right is the result of 700 MHz. Then, the blue legend represents the path loss is smaller, and red represents the greater the path loss. Through the comparison of rendering diagram, it can be seen clearly that the path loss of 700 MHz is obviously less than the loss of 2.6 GHz. It can be concluded that under the same conditions, the smaller the path loss is, the better the coverage effect will be.

Outdoor Remote Simulation
Zhumeila apartments base station cell in Zhujiang New Town area is selected to simulate the outdoor remote coverage of 2.6 GHz and 700 MHz. The electrical level of 700 MHz is reduced to −110 dBm at 1.94 km, and the electrical level of 2.6 GHz is reduced to −110 dBm at 1.48 km. The outdoor remote range of 700 MHz per cell is better than 2.6 GHz, which is more than 30%.

Region Coverage Simulation
The ray tracing simulations of 2.6 GHz and 700 MHz were carried out in this area, and the simulation results are shown in Fig. 7.

The statistical results are shown in Table 5:

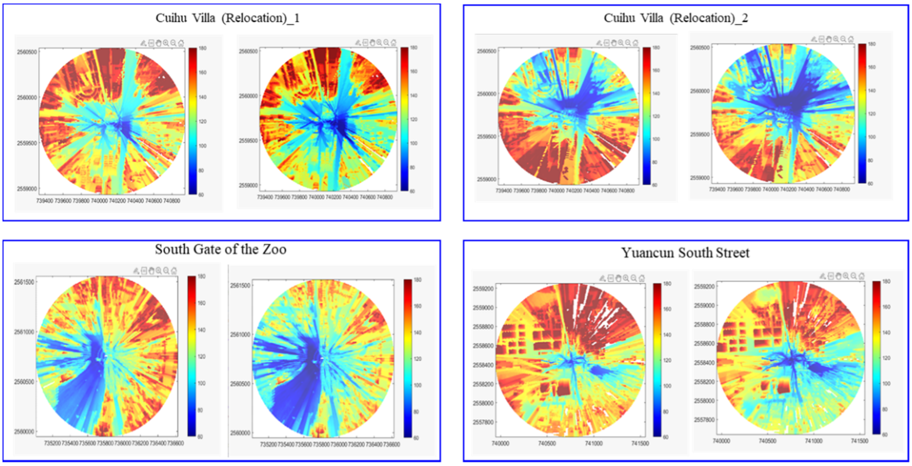

Fig. 5. Path loss rendering results

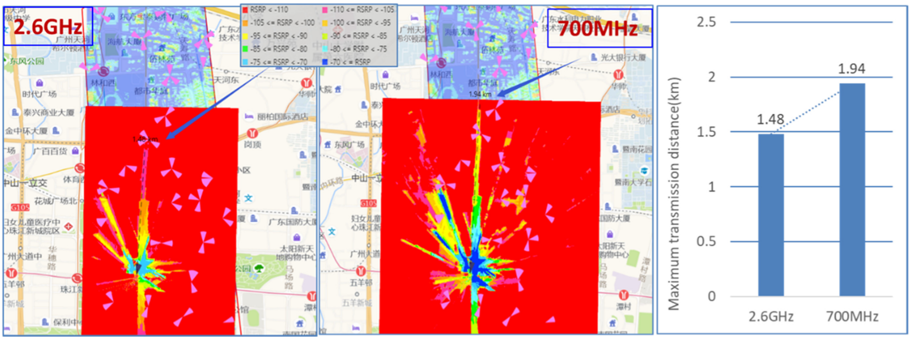

Fig. 6. Comparison of 700 MHz and 2.6 GHz outdoor remote coverage

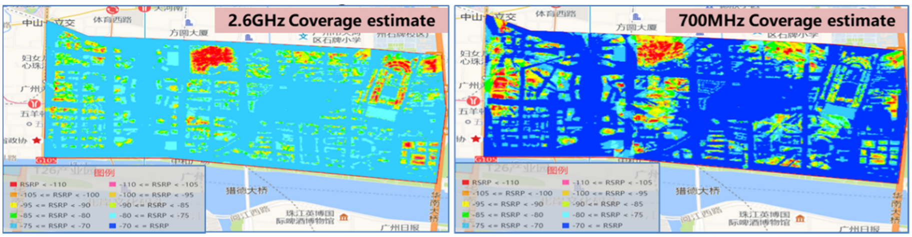

Fig. 7. 3D ray tracing simulation results

Table 5. Statistical results of regional coverage indicators.

Simulated frequency band	Average RSRP (dBm)	RSRP (>=-93dBm) coverage percentage	SINR (>=-3db) compliance rate percentage	RSRP (>=-93dBm) coverage rate percentage and SINR (>=-3db) compliance rate percentage
2.6GHz	-76.02	94.3	54.6	50.1
700MHz	-73.52	93.5	70.6	63.4

According to the simulation results, the prediction effect of 700 MHz area coverage is far better than that of 2.6 GHz. When 700 MHz base stations account for 28% of the number of 2.6 GHz base stations, the coverage effect of 2.6 GHz can be reached and exceeded.

Stereoscopic Building Simulation

Based on LiShuttle ray tracing propagation model and Plannet electronic map, three-dimensional simulation and rendering of buildings in this area are carried out, which using open source 3D rendering technology Cesium. This rendering adopts two methods: floor average and edge average. The floor average rendering is based on the average value of all grid field strength of each floor to render the building, and the edge average method is based on the grid field strength of the building contour to render the building. The results of building stereoscopic simulation are shown in Fig. 8.

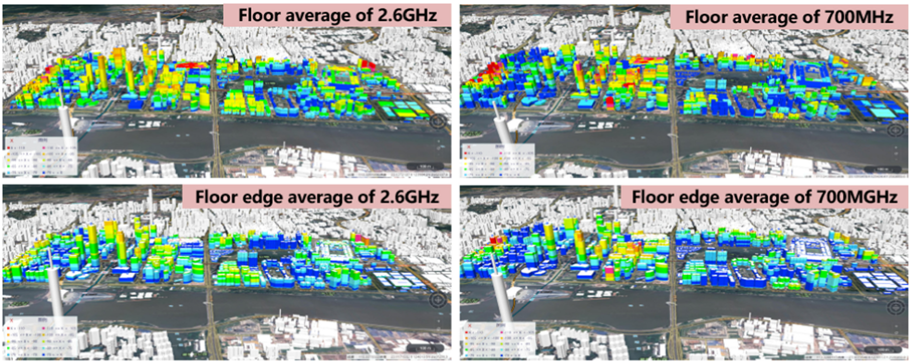

Fig. 8. Building stereoscopic simulation results

It can be seen from the simulation results that the indoor coverage effect of 700 MHz through the outdoor macro base station is obviously better than that of 2.6 GHz. Although in some areas, there are deviations due to the distribution of base stations. By analyzing the simulation results of the buildings in this area, among the total number of the buildings in the area which is 1069, there are 736 buildings with 700 MHz resulting better than bulidings with 2.6 GHz in terms of indoor average and 727 bulidings resulting better than buildings with 2.6 GHz with respect to edge average, accounting for 68.8% and 68.1% respectively.

The typical building Greater China International Trading Market in this area is selected for analysis. The simulation results are shown in Fig. 2, 3, 4, 5 and 6. The average floor RSRP of the building is −96.4 dBm and the average indoor RSRP of 700 MHz is −81.2 dBm. Therefore, the RSRP of 700 MHz is about 15 dBm higher than that of 2.6 GHz (Fig. 9).

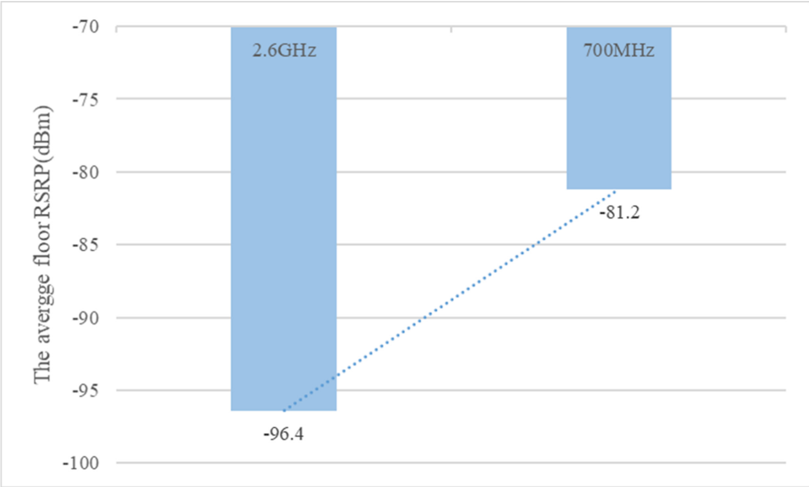

Fig. 9. Results of typical building statistics

4 Conclusion

Based on the traditional ray tracing propagation model LiShuttle, this paper explores the simulation and coverage capability of 5G NR system in 700 MHz frequency band under ultra dense scene, and conducts the comparative analysis with the lowest 5G frequency band 2.6 GHz allocated by our country. According to the simulation analysis, it can be seen that the 700 MHz frequency band link budget will produce significant gains, its coverage distance will be longer when it is extended outdoors, the number of base stations will be greatly reduced to achieve the same coverage effect, and the building can have an excellent coverage effect. All in all, it will have a very big advantage in the future 5G base station construction.

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